Remote Sensing of Surface Soil Moisture[1]

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ABSTRACT

The unique thermal and dielectric properties of water afford two possibilities for remotely sensing the moisture content in the surface layer of the soil. Observations of the diurnal range of surface temperature, the microwave brightness temperature (emissivity) and radar backscatter of the soil have shown correlations of up to 0.9 with the moisture in the surface layer (~5 cm thick). The microwave techniques appear to maintain their sensitivity to moisture variations in the presence of a crop canopy. Observations of microwave brightness temperature from satellite platforms have qualitatively confirmed this sensitivity for a wide range of conditions.

1. Introduction

The unique thermal and dielectric properties of water afford two possibilities for remotely sensing the moisture content in the surface layer of the soil. The large heat capacity and thermal conductivity of water enable moist soils to have a large thermal inertia. This thermal inertia can be remotely sensed by observing the diurnal range of surface temperature.

The dielectric constant for water is an order of magnitude larger than that of dry soils at microwave wavelengths (30 cm$>\lambda>$1 cm). As a result the surface emissivity and reflectivity for the soils at these wavelengths are strong functions of its moisture content. The changes in emissivity can be observed by passive microwave techniques (radiometry) and the changes in reflectivity can be observed by active microwave techniques (radar).

Both of these approaches, thermal and microwave, have been demonstrated in extensive field and aircraft measurements. Correlations of about 0.9 have been obtained between soil moisture in the surface layer (~5 cm thick) and microwave brightness temperatures or diurnal range of surface temperature. The microwave techniques maintain their sensitivity to soil moisture variation in the presence of a crop canopy. Qualitative observations of the passive microwave sensitivity have been made from satellite platforms at wavelengths of 21 and 1.55 cm. Thus, it appears to be possible to monitor the moisture status of the surface soil using these techniques.

Since NASA is planning or proposing spacecraft tests of these approaches this paper will provide an opportunity to present the results on which these proposals are based and to discuss the relative advantages of each method.

2. Thermal methods

The amplitude of the diurnal range of surface temperature for the soil is a function of both internal and external factors. The internal factors are thermal conductivity (K) and heat capacity (C), where $P=(KC)^{\frac{1}{2}}$ defines what is known as "thermal inertia." The external factors are primarily meteorological—solar radiation, air temperature, relative humidity, cloudiness, wind, etc. The combined effect of these external factors is that of the driving function for the diurnal variation of surface temperature. Thermal inertia, then, is an indication of the soil's resistance to this driving force. Since both the heat capacity and thermal conductivity of a soil increase with an increase of soil moisture, the resulting diurnal range of surface temperature will decrease.

The basic phenomena are illustrated in Fig. 1, which presents surface temperatures as measured with a thermocouple for a field versus time, before and after irrigation. These data were obtained at the U. S. Water Conservation Laboratory in Phoenix (Idso *et al.*, 1975).

The solid line in Fig. 1 is the plot of surface temperature before irrigation, and the filled circles reflect the data on the day following irrigation. There is a dramatic difference in the maximum temperature achieved on these two days. On succeeding days the maximum temperature increases as the field dries out.

The summary of results from many such experiments is shown in Fig. 2 where the amplitude of the diurnal range is plotted as a function of the soil moisture as measured at the surface and at 0–1 cm, 0–2 cm and

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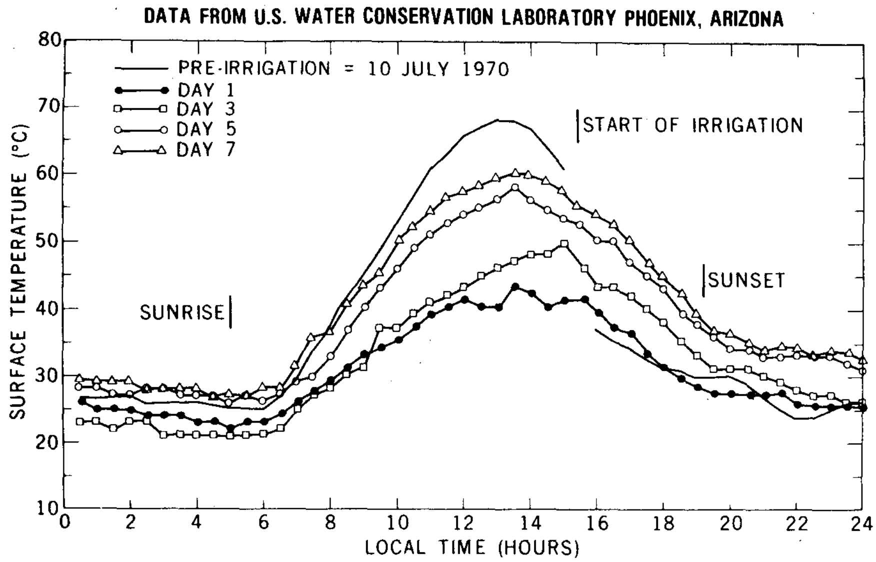

FIG. 1. Diurnal surface temperature variation.

0–4 cm layers. There is a good correlation with the soil moisture in the 0–2 cm and 0–4 cm layers of the soil, and this response is related to the thermal inertia of the soil. Initially, when the surface is moist, the temperatures are *more or less* controlled by evaporation. Once the surface layer dries below a certain level, the temperature will be determined by the thermal inertia of the soil. These results indicate that for this particular soil, the diurnal range of surface temperature is a good measure of its moisture content.

When these measurements are repeated for different soils, there are differences which depend on the soil type. However, there are certain characteristics that are independent of the soil type, and these relate to the evaporation of the water from the soil. Soil physicists have characterized the drying of a soil in three stages:

- The wet stage, where the evaporation is solely determined by the meteorological condition.
- An intermediate or drying stage where it starts out being in the wet stage early in the day, but because there is not a sufficient amount of water in the soil to meet the evaporative demand, the evaporation rate falls off.
- The dry stage, where evaporation is solely determined by the molecular transfer properties of water within the soil.

There is a striking change in both the albedo and the evaporation rate as the soil dries during the transition from the wet stage to drying stage.

Temperature measurements were repeated for different soil types. The soils ranged from sandy or light soils to heavy clay soils. It is clear that for a given diurnal temperature difference, there can be a wide range of moisture content for these soils (Idso *et al.*, 1975).

However, the ΔT values observed as the soils dried through the transitions between the stages mentioned above were approximately the same for all of the soil types studied. Thus it has been concluded (Idso *et al.*, 1975) that while the relation between ΔT and moisture content depends on soil type, the relation between ΔT and pressure potential (the tension with which water is held by soil particles) is independent of soil type. This is the basis for expressing moisture values as a percent of field capacity (FC), where field capacity is taken to be the moisture content at the $-\frac{1}{3}$ bar pressure potential.

It should be emphasized that these experiments were all made in a field, using thermocouples, and were not remotely sensed. In March 1975, an experiment was performed in which remotely sensed thermal infrared temperatures from an aircraft platform were compared with the *in situ* thermocouple measurements over a 5-day period. There was good agreement between the thermocouple measurements and the remotely sensed radiation measurements made from the aircraft (Reginato *et al.*, 1976; Schmugge *et al.*, 1978), indicating that the conclusions based on the thermocouple measurements would also be valid for radiation temperature observation.

In Fig. 3 the results from both the field experiments (from Fig. 2) and the aircraft experiments are presented. The field results are expressed as a percent of field capacity so they can be compared with the aircraft results obtained over a wide range of soil textures. The good agreement between the field and aircraft results indicate that the results based on the field measurements can be extrapolated to the remote sensing technique also.

This technique is not applicable to fields with a vegetative canopy. However, the difference between canopy temperature and ambient air temperature has

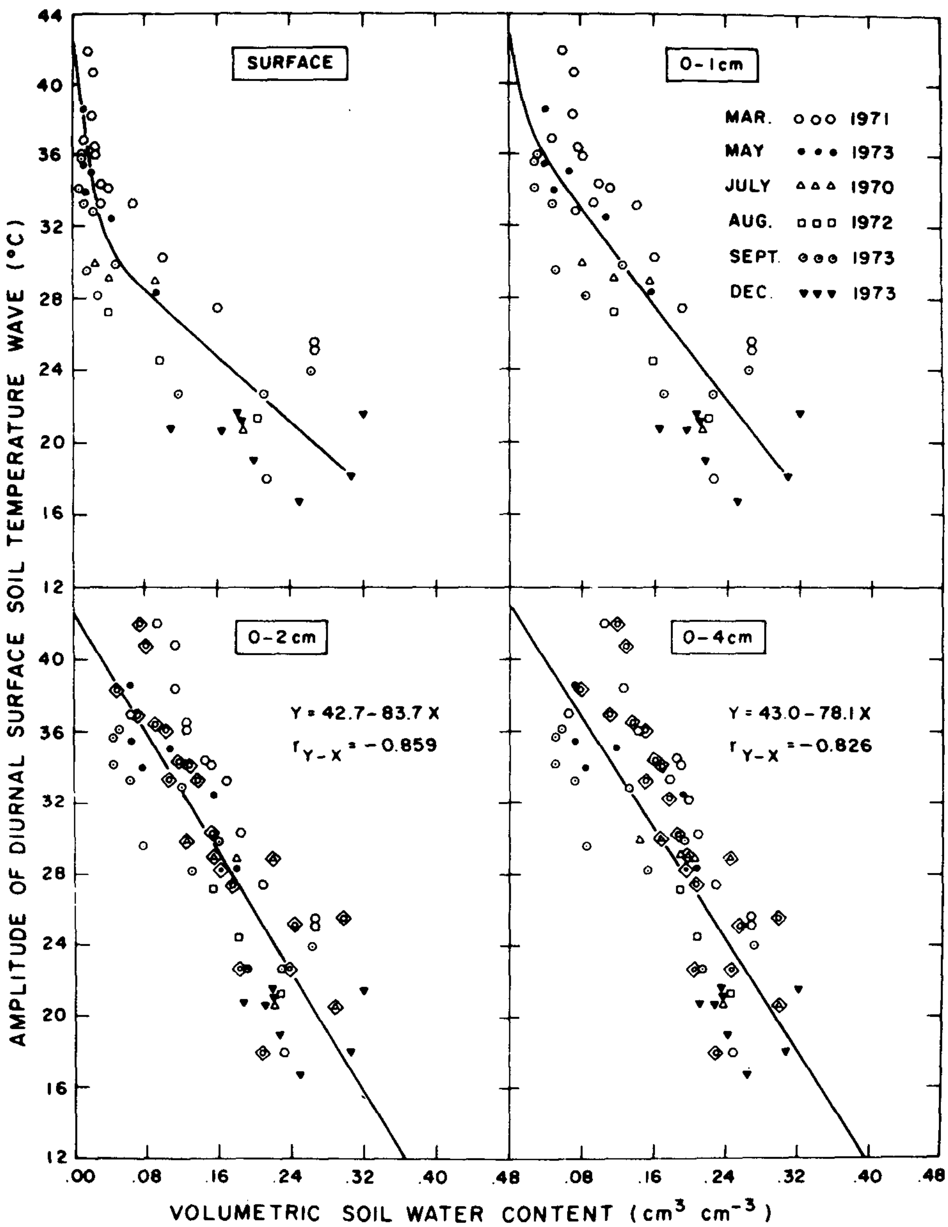

FIG. 2. Summary of results for the diurnal temperature variation versus soil moisture. From Idso *et al.* (1975).

been shown to be an indicator of crop water use (Jackson *et al.*, 1977), thus extending the usefulness of the thermal IR approach.

This approach will be studied further by additional high altitude aircraft flights and by the Heat Capacity Mapping Radiometer launched on the first Applications Explorer Satellite in April 1978. This sensor has two channels (10–12 μm and 0.5–1.1 μm), the latter for measuring surface albedo. The spatial resolution will be 0.6 km. The satellite will be in a 600 km sun-synchronous orbit with a 1400 LST equator crossing to observe the maximum surface temperature. The minimum will be observed either 12 h before or after to provide the diurnal range. This coverage will be repeated every eight days.

3. Microwave methods

a. Soil dielectric properties

As noted in the Introduction the dielectric properties of a soil are strongly dependent on its moisture content because of the large dielectric constant for water, approximately 80 as compared with 3 or 4 for dry soils. This dependence is shown in Fig. 4 which presents the

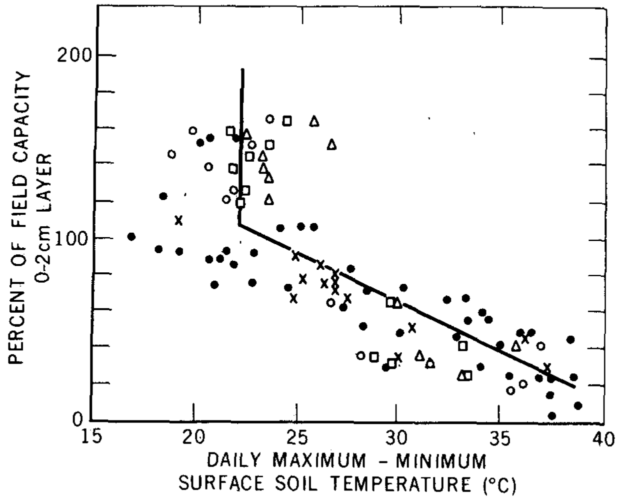

FIG. 3. Plot of ΔT versus soil moisture in the 0–2 cm layer. The symbols represent the different types of temperature measurement: (●), (□), surface thermocouple; (○), hand-held radiometer; (△), aircraft data over test plot; (×), aircraft data over the general agricultural fields. [(●), (□), (○), (△) from Reginato *et al.* (1976); (×) from Schmugge *et al.*, (1978).]

results of laboratory measurements at wavelengths of 21 and 1.55 cm. The wavelength dependence is due to the difference in the dielectric properties of water at the two wavelengths.

At low levels there is a slow increase with soil moisture but above a certain point there is a sharp increase in the slope of the curve which is due to the behavior or the water in the soil. When water is first added to a soil it is tightly bound to the soil particles and in this state the water molecules are not free to become aligned and the dielectric properties of this water are similar to those of ice. As the layer of water around the soil particle becomes larger, the binding to the particle decreases and the water molecules behave as they do in the liquid, hence the greater slope at the higher soil moisture values. The transition depends on the soil texture, i.e., particle size distribution being lower for a sand and large for a clay. This effect has been demonstrated in laboratory measurements of the dielectric constant (Lundien, 1971; Newton, 1976).

Recall that the dielectric constants of the medium describe propagation characteristics for an electromagnetic wave in the medium. Therefore, they determine the emissive and reflective properties for a smooth surface.

b. Passive microwave response to soil moisture

A microwave radiometer measures the thermal emission from the surface and at these wavelengths the intensity of the observed emission is essentially proportional to the product of the temperature and emissivity of the surface (Rayleigh-Jeans approximation). This product is commonly referred to as brightness temperature. All our results will be expressed as brightness temperatures (T_B). The value of T_B observed by a radiometer at a height h above the ground is

$$T_B = \tau(rT_{\text{sky}} - (1-r)T_{\text{surf}}) + T_{\text{atm}}, \qquad (1)$$

where r is the surface reflectivity and τ the atmospheric transmission. The first term is the reflected sky brightness temperature which depends on wavelength and atmospheric conditions; the second term is the emission from the surface ($1-r=e$, where e is the emissivity); and the third term is the contribution from the atmosphere between the surface and the receiver. At the longer wavelengths, i.e., these best suited for soil moisture sensing, the atmospheric effects are minimal and will be neglected in this discussion.

The range of dielectric constant presented in Fig. 4 produces a change in emissivity from greater than 0.9 for a dry soil to less than 0.6 for a wet soil, assuming an isotropic soil with a smooth surface. This change in emissivity for a soil has been observed by truck-mounted radiometers in field experiments (Poe *et al.*, 1971; Newton, 1976), and by radiometers in aircraft (Schmugge *et al.*, 1974) and satellites (Eagleman and Lin, 1976). In no case were emissivities as low as 0.6 observed for real surfaces. It is believed that this is primarily due to the effects of surface roughness which generally has the effect of increasing the surface emissivity.

As can be seen in Fig. 4 there is a greater range of dielectric constant for soils at the 21 cm wavelengths. This fact combined with a larger soil moisture sampling

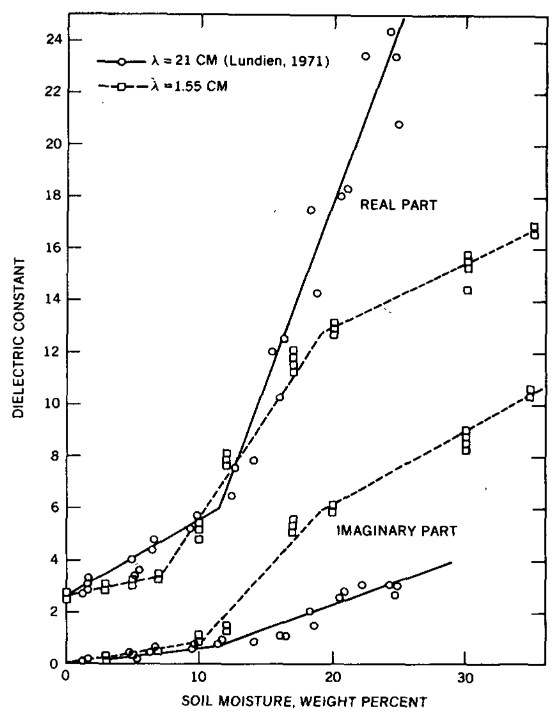

FIG. 4. Dependence of the soil's dielectric constant on its moisture content.

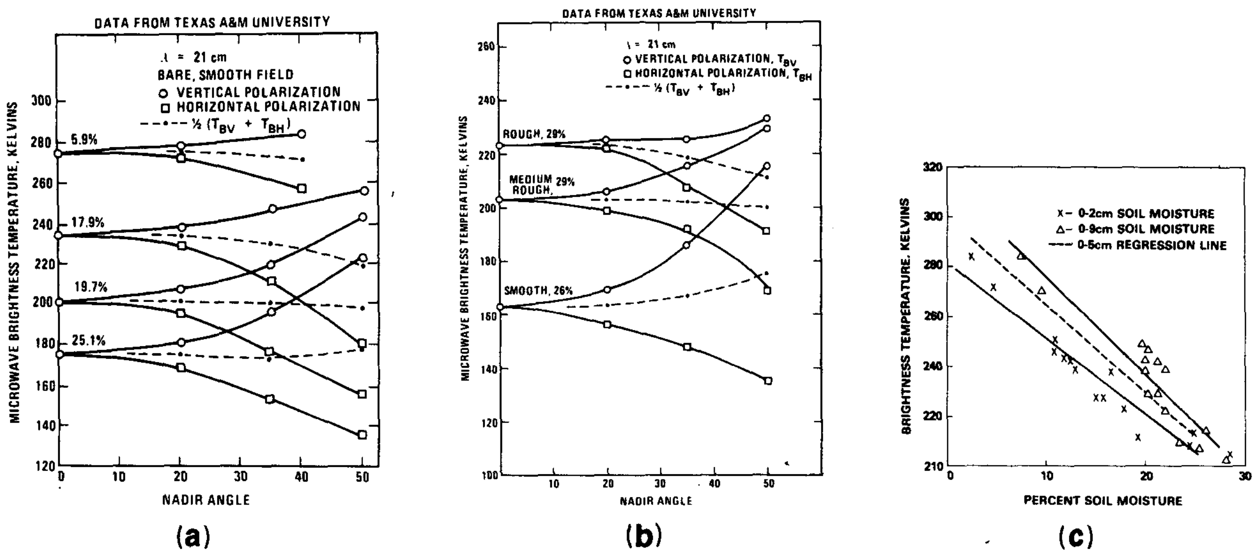

Fig. 5. Results from field measurements performed at Texas A&M University: (a) T_B versus angle for different moisture levels; (b) T_B versus angle for different surface roughness at about the same moisture level; (c) T_B versus soil moisture in different layers for the medium rough field (Newton, 1976).

depth and better ability to penetrate a vegetative canopy make the longer wavelength sensors better suited for soil moisture sensing.

In Fig. 5, the field measurements of Newton (1976) are plotted versus angle of observation for various moisture contents and for three levels of surface roughness. The horizontal polarization is that for which the electric field of the wave is parallel to the surface and the vertical polarization is perpendicular to it.

These results indicate the effect of moisture content on the observed values of T_B and the effect of surface roughness which is to increase the effective emissivity at all angles and to decrease the difference in T_B for the two polarizations at the larger angles.

For the smooth field there is a 100 K change in T_B in going from wet to dry soils and it is clear that this range is reduced by surface roughness. The effect of the roughness is to decrease the reflectivity of the surface and thus to increase its emissivity. For a dry field the reflectivity is already small (<0.1) so that the resulting increase in emissivity is small. As seen in Fig. 5b surface roughness has a significant effect for wet fields where the reflectivity is larger (~ 0.4). Thus the range of T_B for the rough field is reduced to about 60 K. The smooth and rough fields represent the extremes of surface conditions that are likely to be encountered, e.g., the rough surface was on a field with a heavy clay soil (clay fraction $>60\%$) that had been

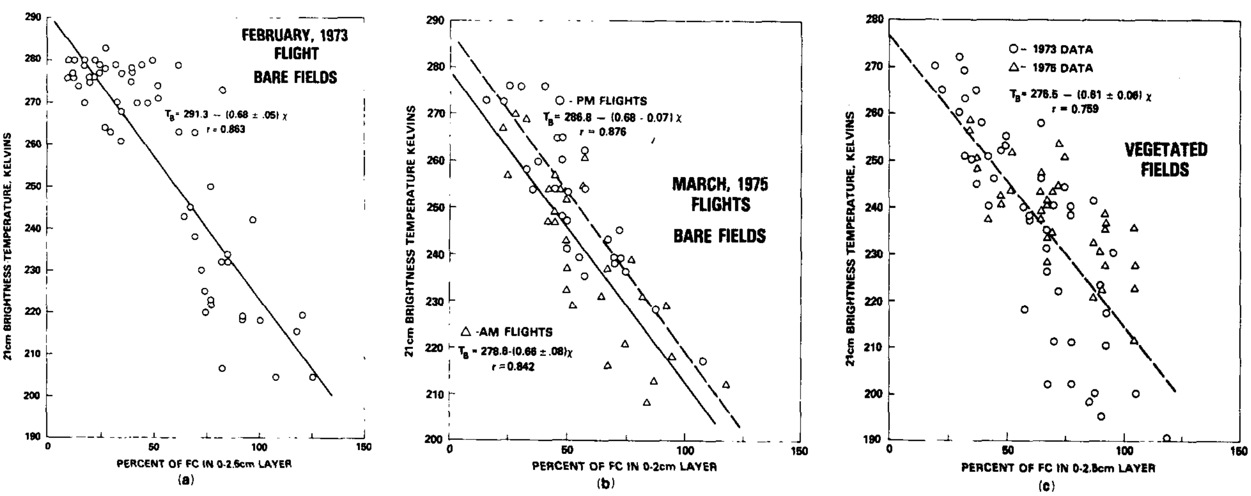

Fig. 6. Aircraft observations of T_B over agricultural fields around Phoenix: (a) bare field results from 1973 flight; (b) bare field results from 1975 flights; (c) vegetated field results from both years.

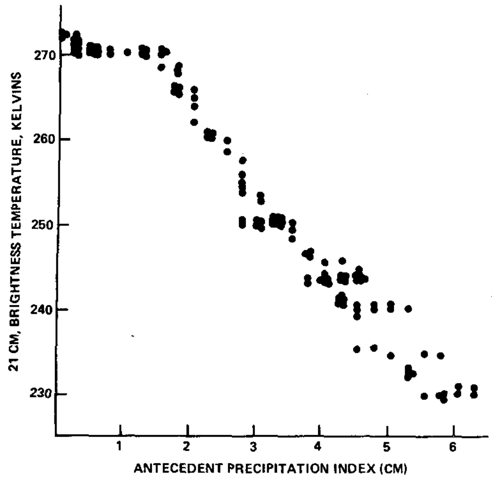

FIG. 7. Skylab observations of T_B at 21 cm compared with antecedent precipitation over Texas and Oklahoma (McFarland, 1976).

deep plowed which produced large clods. Therefore the medium rough field, with a T_B range of 80 K, is probably more representative of the average surface roughness condition that will be encountered. Another important observation from Fig. 5 is that the average of the vertical and horizontal T_B's is essentially independent of angle out to 40°. This indicates that the sensitivity of this quantity, $\frac{1}{2}(T_{BV}+T_{BH})$, to soil moisture will be independent of angle. This factor will be useful if the radiometer is to be scanned to provide an image.

When the brightness temperatures for the medium rough field are plotted versus soil moisture in the 0–2 cm layer there is an approximate linear decrease of T_B (Fig. 5c). As the thickness of the layer increases both the slope and intercept of the linear regression result also increase. This is because the moisture for the high T_B cases increases, while it remains essentially the same for the low T_B or wet cases. This type of behavior was also seen in the results obtained from aircraft platforms and has led us to conclude that the soil moisture sampling depth is in the 2–5 cm range for the 21 cm wavelength. This is in agreement with the predictions of theoretical results for radiative transfer in soils (Wilheit, 1978; Burke *et al.*, 1978).

The results from aircraft experiments are summarized in Fig. 6 where the results from flights in February 1973 (Schmugge *et al.*, 1976) and March 1975 (Schmugge, 1976) over Phoenix, Arizona, are presented. The T_B values are plotted versus soil moisture expressed as a percent of field capacity as was done for the thermal inertia case (Fig. 3) to normalize the effect of soil texture differences. The agreement of the slopes for the three regressions indicates that the results are repeatable. The differences in the intercepts are due to the differences in soil temperature. This is particularly evident in the difference between the 1975 morning and afternoon results. Also, note that the range of T_B (80 K) is in good agreement with the medium rough field of Fig. 5.

The effect of a vegetative canopy will be that of an absorbing layer that depends on the amount of the vegetation and the wavelength of observations. In Fig. 6c the results for vegetated fields from the two years are presented. The vegetation was either alfalfa or wheat with the wheat being 20–30 cm high in 1973 and 50–60 cm high for the 1975 data. The slope of the curve is in good agreement with those for the bare fields. The intercept is lower due to the cooler soil temperatures. Thus the sensitivity to soil moisture is maintained through the moderate vegetative canopies considered here. This result is supported by the field measurements of Newton (1976) who found the sensitivity maintained through 125 cm of closely planted sorghum.

As has been reported by McFarland (1976) and by Eagleman and Lin (1976), the sensitivity of the 21 cm radiometer to soil moisture has already been demonstrated from space during the Skylab mission. McFarland showed a definite relationship between the Skylab 21 cm brightness temperatures and the Antecedent Precipitation Index (API). Fig. 7 presents these results for a pass starting over the Texas and Oklahoma panhandles and proceeding to the southeast toward the Gulf of Mexico. Each point plotted is the observed brightness temperature and the API calculated from all the rain gages within the 110 km footprint. Since there is considerable overlap for the radiometer footprints presented here, this plot should be considered as a comparison of the running average of T_B with API. As such it shows the sensitivity of spaceborne radiom-

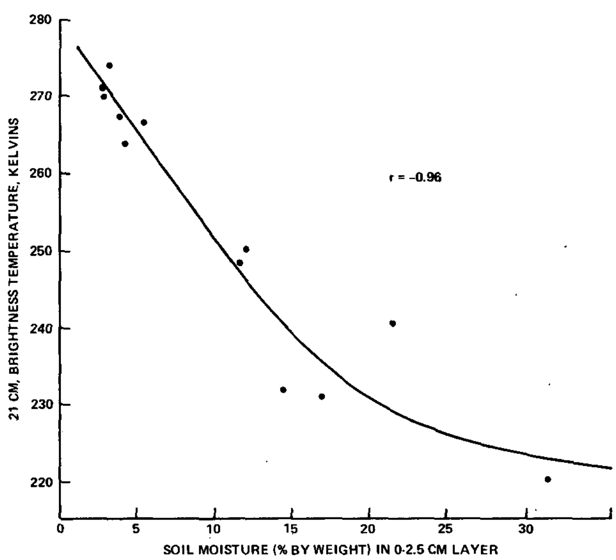

FIG. 8. Skylab observation of T_B at 21 cm compared with soil moisture estimates from five passes over the southern Great Plains (Eagleman and Lin, 1976).

eter to the soil moisture variations caused by the rainfall.

Eagleman and Lin (1976) carried the analysis of the Skylab data a step further, and compared the brightness temperature with estimates of the soil moisture over the radiometer footprint. The soil moisture estimates were based on a combination of actual ground measurements and calculations of the soil moisture using a climatic water balance model. A summary of their results is presented in Fig. 8 for 12 footprints obtained during five different Skylab passes over the states of Texas, Oklahoma and Kansas. The correlation coefficient for these 12 data points is 0.96, which is very good considering the difficulty of obtaining soil moisture information over a footprint of such a size and considering the fact that the brightness temperature was averaged over the wide range of cultural conditions that occurred over the area.

These results from space supported by the more detailed aircraft and ground measurements presented earlier give strong support to the possibility of using microwave radiometers for soil moisture sensing. Therefore, to pursue this technique further, NASA is giving strong consideration to flying a 21 cm radiometer on a future mission to monitor soil moisture variations globally. A candidate system would have a 10 m$\times$10 m antenna which provides 20–40 km spatial resolution from a 800 km orbit. The proposed launch date for this mission is the mid 1980's.

c. *Active microwave response to soil moisture*

The backscattering from an extended target, such as a soil medium, is characterized in terms of the target's scattering coefficient σ°. Thus, σ° represents the link between the target properties and the scatterometer responses. For a given set of sensor parameters (wavelength, polarization and incidence angle relative to nadir), σ° of bare soil is a function of the soil surface roughness and dielectric properties which depends on the moisture content. The variations of σ° with soil moisture, surface roughness, incidence angle and observation frequency have been studied extensively in ground-based experiments conducted by scientists at the University of Kansas (Batlivala and Ulaby, 1977) using a truck mounted 1-18 GHz active microwave system.

To understand the effects of look angle and surface roughness consider the plots of σ° versus angle presented in Fig. 9 for five fields with essentially the same moisture content but with considerably different surface roughness. At the longest wavelength (1.1 GHz, Fig. 9a), σ° for the smoother fields is very sensitive to incidence angle near nadir, while for the rough field σ° is almost independent of angle. At an angle of about 5° the effects of roughness are minimized. As the wavelength decreases (Figs. 9b and 9c) all the fields appear rougher, especially the smooth field, and as a result the intersection point of the five curves moves out to larger angles. At 4.25 GHz the intersection occurs at 10°, and it was this combination of angle and frequency that yielded the best sensitivity to soil moisture independent of roughness.

These experiments were performed in both 1974 and 1975, the first on a field with high clay content (62%), the second with a lower clay content. Although both experiments provided the same specifications of the radar parameters for soil moisture sensing, i.e., frequency around 4.75 GHz and a 7–17° nadir angle,

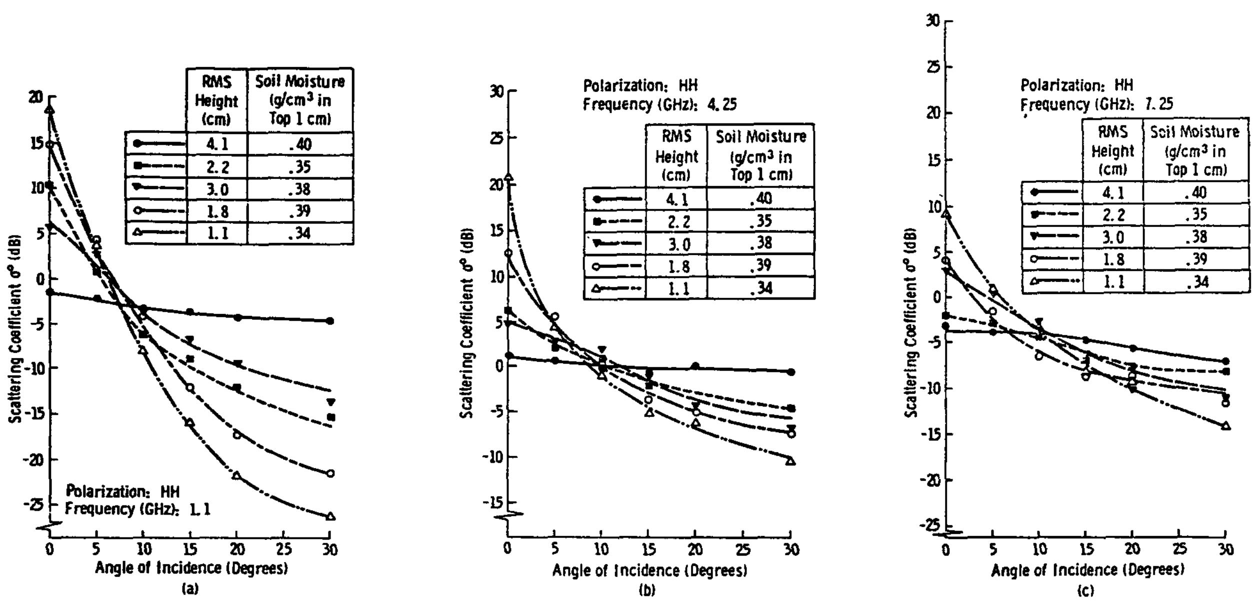

Fig. 9. Angular response of scattering coefficient for the five fields in high levels of moisture content: (a) L-band (1.1 GHz); (b) C-band (4.25 GHz); (c) X-band (7.25 GHz). 1975 soil moisture experiment (Batlivala and Ulaby, 1977).

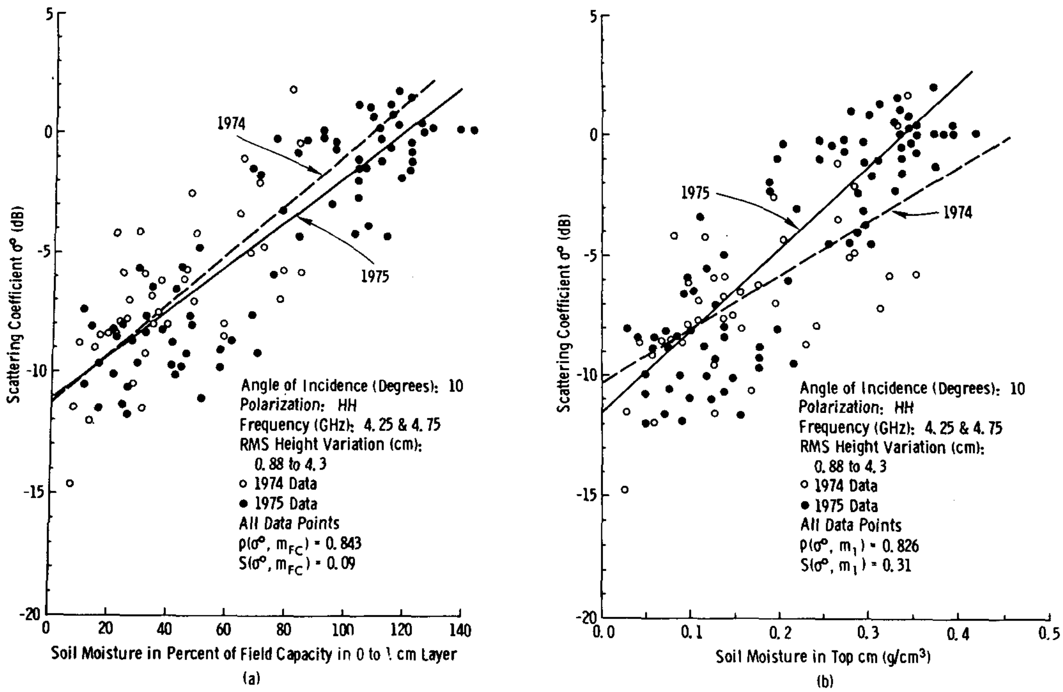

FIG. 10. Backscattering coefficient plotted as a function of soil moisture given (a) in percent of field capacity of the top 1 cm and (b) volumetrically in the top 1 cm. 1974 and 1975 bare soil experiment data are combined (Batlivala and Ulaby, 1977).

the observed sensitivity of σ° to soil moisture was different for the two experiments (Fig. 10b). When the soil moisture content is expressed as a percent of field capacity to account for textural differences, the sensitivities became almost identical (Fig. 10a) with a correlation of 0.84. This dependence on the percent of field capacity is similar to that observed with the thermal inertia and passive microwave techniques.

There have been some recent experiments studying the active microwave approach from aircraft and the results should be available in the near future. In 1978 there will be additional experiments performed with a scatterometer operating near the optimum frequency and should demonstrate the capabilities of this approach.

3. Discussion

At the present time none of the three methods presented here has the clear advantage for being the preferred method of remote sensing of soil moisture. The thermal IR approach has the advantage of providing useful thermal data that may be an indicator of crop status and is capable of providing soil moisture data at high spatial resolutions. However, the usefulness of this approach is lost in the presence of cloud cover. The ability of the microwave sensors to penetrate non-raining clouds makes them very attractive for use as soil moisture sensors. The passive microwave technique has been demonstrated by both aircraft and spacecraft instruments, but the spatial resolution is limited by the size of the antenna which can be flown. For example, at a wavelength of 21 cm, a 10 m×10 m antenna is required to yield 20 km resolution from a satellite altitude of 800 km. It is possible to make use of the coherent nature of the signal in active microwave systems (Synthetic Aperture Radar, SAR) to obtain better spatial resolutions (Moore, 1975). However, the capabilities of such systems for soil moisture sensing remain to be demonstrated from either aircraft or spacecraft platforms. Also, the strong effects of incidence angle and surface roughness makes the unambiguous determination of soil moisture difficult with this type of sensor.

While it is clear that no one system will satisfy all requirements that may be desirable for a soil moisture sensing system (i.e., frequent, high-resolution coverage on a global basis), a microwave radiometer with the characteristics mentioned above would provide wide area coverage with 10–20 km resolution every two or three days. This system could be supplemented with either the thermal IR or radar high-resolution data on a sampling basis.

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